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Arctic river-runoff: mean residence time on the shelves and in the halocline

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Abstract—The mean residence time of river-runoff on the shelves and in the halocline of the Arctic Ocean is estimated from salinity and tracer data (tritium, ^{3}He and the $^{18}O/^{16}O$ ratio). These estimates are derived from comparison of apparent tracer ages of the halocline waters using a combination of tracers that yield different information: (1) the tritium "vintage" age, which records the time that has passed since the river-runoff entered the shelf; and (2) the tritium/^{3}He age, which reflects the time since the shelf waters left the shelf. The difference between the ages determined by these two methods is about 3–6 years. Correction for the initial tritium/^{3}He age of the shelf waters (about 0.5–1.5 years) yields a mean residence time of the river-runoff on the shelves of the Siberian Seas of about 3.5 ± 2 years.

INTRODUCTION

THE upper water column in the Arctic Ocean is dominated by a strong halocline that separates the fresh Polar Surface Water from the underlying Atlantic-derived waters. The halocline is formed by freshwater added from river-runoff or sea ice meltwater to the surface waters. The halocline waters store a significant amount of freshwater which finally is exported from the Arctic Ocean through Fram strait via the East Greenland Current. Part of the freshwater transported in the East Greenland Current mixes into the center of the convective gyres of the Greenland and Labrador Seas, and influences in this way the delicate salinity balance of their surface waters. Variations in the supply of freshwater to the surface waters of the gyres may have significant influence on the strength of deep convection (AAGAARD and CARMACK, 1989), on the associated deep water formation (e.g. GREENLAND SEA PROJECT GROUP, 1990; SCHLOSSER *et al.*, 1991), and thus on the deep circulation of the world ocean.

The salinity balance of the Arctic Ocean surface waters is influenced by the supply of freshwater from rivers discharging onto the Arctic shelves. The total freshwater inventory of the shelves exceeds the annual freshwater input (e.g. HANZLICK and AAGAARD, 1980) and they act as a short-term buffer, moderating variations in the amount and composition of the freshwater. The runoff signal is also modified by mixing with halocline water and

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sea ice meltwater during transport from the shelves to Fram Strait. Both factors have to be known for a proper understanding or the influence of variations in Arctic river-runoff on the salinities of the central gyres in the Greenland/Norwegian/Iceland and Labrador Seas.

Previously, the mean residence time of shelf waters in the Arctic Ocean has been determined on the basis of mass balances (e.g. HANZLICK and AAGAARD, 1980; AAGAARD and COACHMAN, 1975). In this contribution we use tracer data from the Arctic halocline to derive an independent estimate of the mean residence time of the shelf waters in the Arctic Ocean.

METHOD

Our principle approach is to compare various tracer derived ages of halocline waters known to be formed on the shelves of the Arctic Ocean (e.g. AAGAARD *et al.*, 1981; JONES and ANDERSON, 1986). In the Eurasian Basin, halocline waters consist of a mixture of Atlantic water and a freshwater component (river-runoff and sea ice meltwater). Certain tracers delivered to the shelf by river-runoff start to "age" at the time they enter the shelf. Other tracers are in contact with the atmosphere on the shelf and their clock is set to zero only when they leave the shelf and submerge below Arctic Ocean surface water or ice cover. We can use the difference between these two tracer-derived ages to determine the mean residence time of the river-runoff component on the shelf.

ÖSTLUND and HUT (1984) pointed out that the combination of salinity, tritium and ^{18}O can be used to distinguish between river-runoff and sea ice meltwater contained in the freshwater component of the Arctic halocline and to determine the mean age of the river-runoff component. In their approach, they first use salinity and ^{18}O to calculate the fractions of river-runoff and sea ice meltwater in the individual water samples. In a second step they calculate the tritium concentration of the river-runoff component using a hydrological model and compare this value to the tritium concentrations as a function of time in the Siberian rivers (estimated by ÖSTLUND, 1982) to obtain the so-called "tritium vintage age". Applying this method to halocline waters yields an estimate of the mean time that has passed since the river-runoff fraction contained in a water parcel of the halocline was discharged onto the shelf. This time is a measure for the total time spent on the shelf as well as the travel time from the shelf edge to the sampling site.

The tritium/^{3}He age is set to zero in a different way. ^{3}He formed in the shelf waters by tritium decay is lost to a large degree to the atmosphere by gas exchange. Thus, the tritium/^{3}He age is close to zero for shelf waters. The "tritium/^{3}He clock" is started at the time when the shelf waters flow into the interior basin and gas exchange with the atmosphere is suppressed by sea ice and/or overlying water layers. Tritium/^{3}He ages of the Arctic halocline therefore should be lower than the tritium vintage ages. The same should hold for all ages derived from gases dissolved in seawater (e.g. CFCs). The few published data are in agreement with this concept (ÖSTLUND and HUT, 1984; ÖSTLUND *et al.*, 1982; SCHLOSSER, 1985; SCHLOSSER *et al.*, 1990; WALLACE and MOORE, 1985; WALLACE *et al.*, 1987, 1992).

SAMPLE COLLECTION AND MEASUREMENT

The data used in this study were collected during the 1987 cruise of the German research icebreaker *Polarstern* to the Nansen Basin of the Arctic Ocean. During this cruise, a

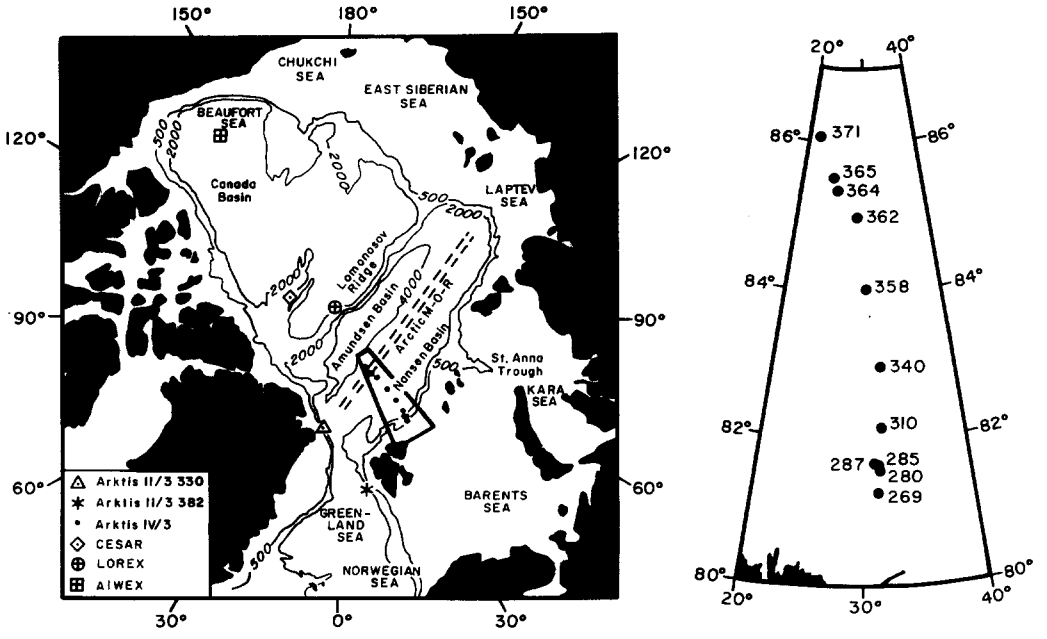

Fig. 1. Geographic positions of the ARK IV/3 stations.

hydrographic section across the Nansen Basin included sampling for a variety of tracers (for a detailed description of the cruise, see PSSP, 1988; ANDERSON *et al.*, 1989). Here we use tritium, ^{3}He and ^{18}O data from a section reaching from the Barents Shelf to the Gakkel Ridge (Fig. 1).

All tritium/^{3}He and part of the ^{18}O samples were measured at the Institute for Environmental Physics at the University of Heidelberg. Most of the ^{18}O samples were measured at the Lamont–Doherty Earth Observatory. Tritium samples were measured mass spectrometrically using the ^{3}He ingrowth technique (BAYER *et al.*, 1989). Precision of the measurements is about ±2%. Tritium data are reported in tritium units (TU). One TU means a tritium to hydrogen ratio of 10^{-18}. ^{3}He/^{4}He ratios were measured with a precision of about ± 0.2% and are reported in the δ notation where δ^3He means the percent deviation of the ^{3}He/^{4}He ratio of a sample from that of an air standard (^{3}He/^{4}He ratio: 1.384×10^{-6}; CLARKE *et al.*, 1976). ^{18}O measurements were performed on a commercial mass spectrometer after equilibration of CO_2 with the water sample. ^{18}O results are reported in the δ notation where $\delta\ ^{18}$O is the per mill. deviation of the ^{18}O/^{16}O ratio of the sample from that of SMOW (Standard Mean Ocean Water). Precision of the Heidelberg ^{18}O data is typically ±0.07% while precision of the L-DGO ^{18}O data is about ±0.02–0.03%.

HYDROGRAPHIC FEATURES

The halocline waters extend throughout the Arctic Ocean below a relatively homogeneous surface layer with temperatures close to the freezing point of seawater and above a

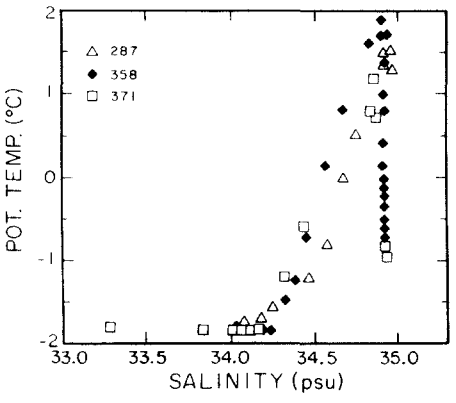

Fig. 2. Potential temperature versus salinity plot for stations from the southern (287), central (358) and northern (371) part of the 1987 *Polarstern* section (for geographic positions, see Fig. 1).

distinct intermediate temperature maximum caused by an advective core of Atlantic water (AAGAARD *et al.*, 1981). The halocline waters are formed and maintained by advection of shelf waters into the central basins (AAGAARD *et al.*, 1981). JONES and ANDERSON (1986), using chemical properties in addition to temperature and salinity data, distinguished between upper and lower halocline waters. The upper halocline waters are characterized by salinities of about 33.1 (psu), temperatures close to the freezing point of seawater and distinct nutrient maxima, while the lower halocline waters have salinities of about 34.25, temperatures close to the freezing point of seawater and a pronounced NO minimum (see also JONES *et al.*, 1991). There are indications that the upper halocline waters originate in the Chukchi Sea while the lower halocline waters are formed in the Barents and Kara seas (e.g. JONES and ANDERSON, 1986; JONES *et al.*, 1991).

Temperature/salinity information from selected stations of the 1987 *Polarstern* section (Fig. 2) indicates that the upper halocline is more or less completely missing in our Nansen Basin section. The lower salinities observed at the northern end of the section (Sta. 371) are due to the influence of increased river-runoff. The halocline waters therefore fall around a more or less linear *T/S* line between the Atlantic water and the core of lower halocline waters as defined by JONES and ANDERSON (1986).

RESULTS

$\delta\ ^{18}O$ values increase to the south and with depth to reach a maximum of about 0.3% at about 300–500 m, i.e. in the core of the Atlantic Water (Fig. 3a and 3c; for comparison with salinity, see Fig. 3b). The surface values are relatively high on the Barents Shelf (about 0.15% at Sta. 269; Fig. 3a) and decrease with latitude to reach minimum values of about −1.6% at sta. 371. This trend in the ^{18}O pattern reflects the higher runoff fraction in the surface waters of the central basin. Below the Atlantic water, $\delta\ ^{18}O$ values are more or less constant to a depth of about 2500 m. At this depth there seems to be a slight increase in $\delta\ ^{18}O$ by about 0.05–0.1% (Fig. 3c). The 2500 m isobath is close to the sill depth separating the Arctic Ocean from the Greenland Sea. Therefore, the decrease in $\delta\ ^{18}O$ above 2500 m might mark the influence of lower salinity waters transported from the Greenland/Norwegian seas into the Arctic Ocean.

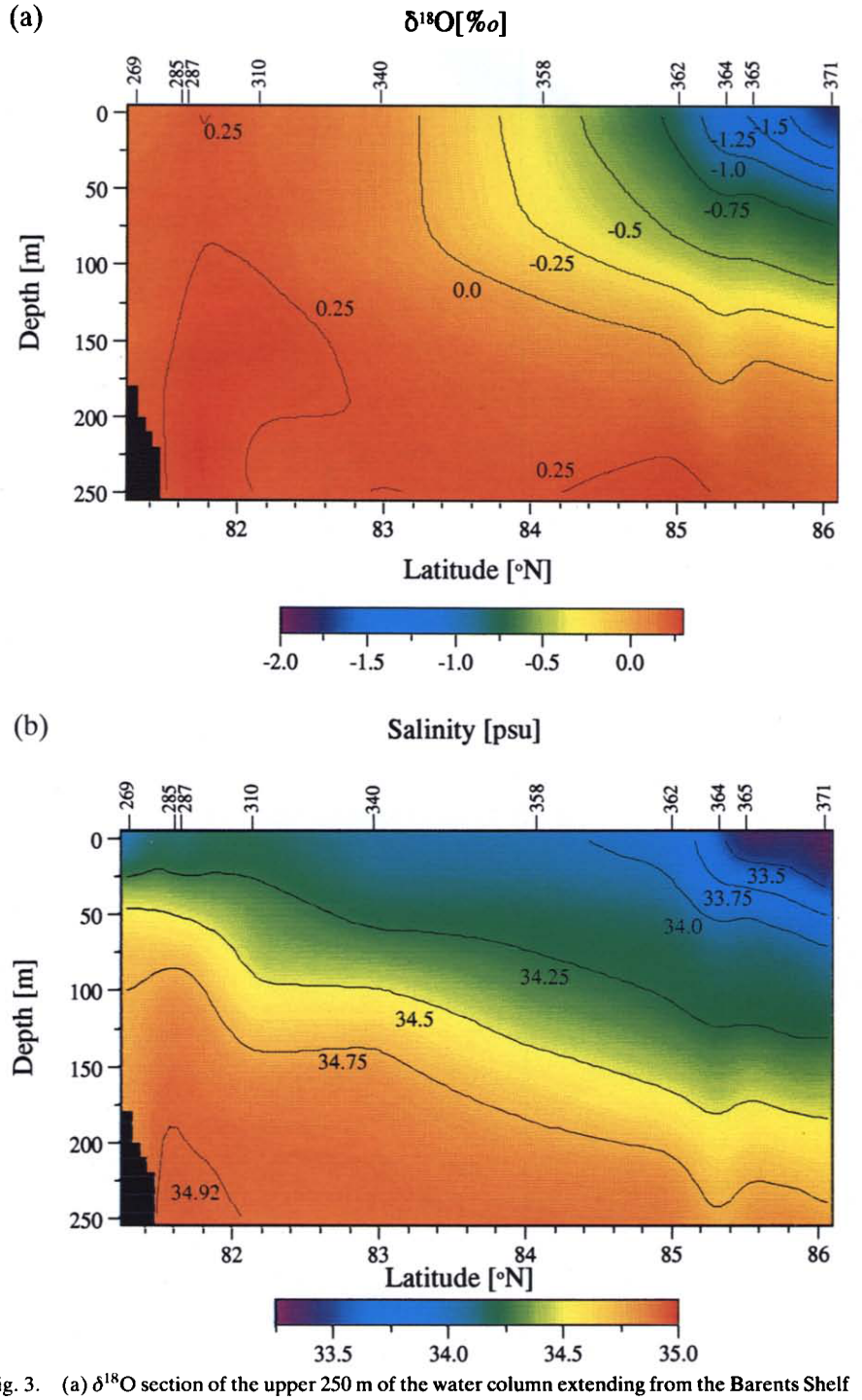

Fig. 3. (a) $\delta^{18}O$ section of the upper 250 m of the water column extending from the Barents Shelf (Sta. 269) to the Gakkel Ridge (Sta. 371; for geographical position of the stations, see Fig. 1). (b) Same as (a) for salinity. (c) $\delta^{18}O$ versus depth plot of Sta. 358 extending over the entire water column.

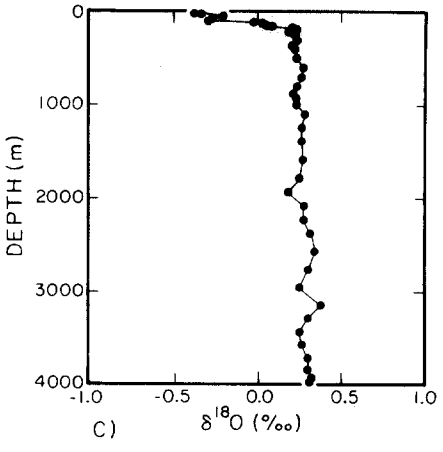

Fig. 3. *Continued.*

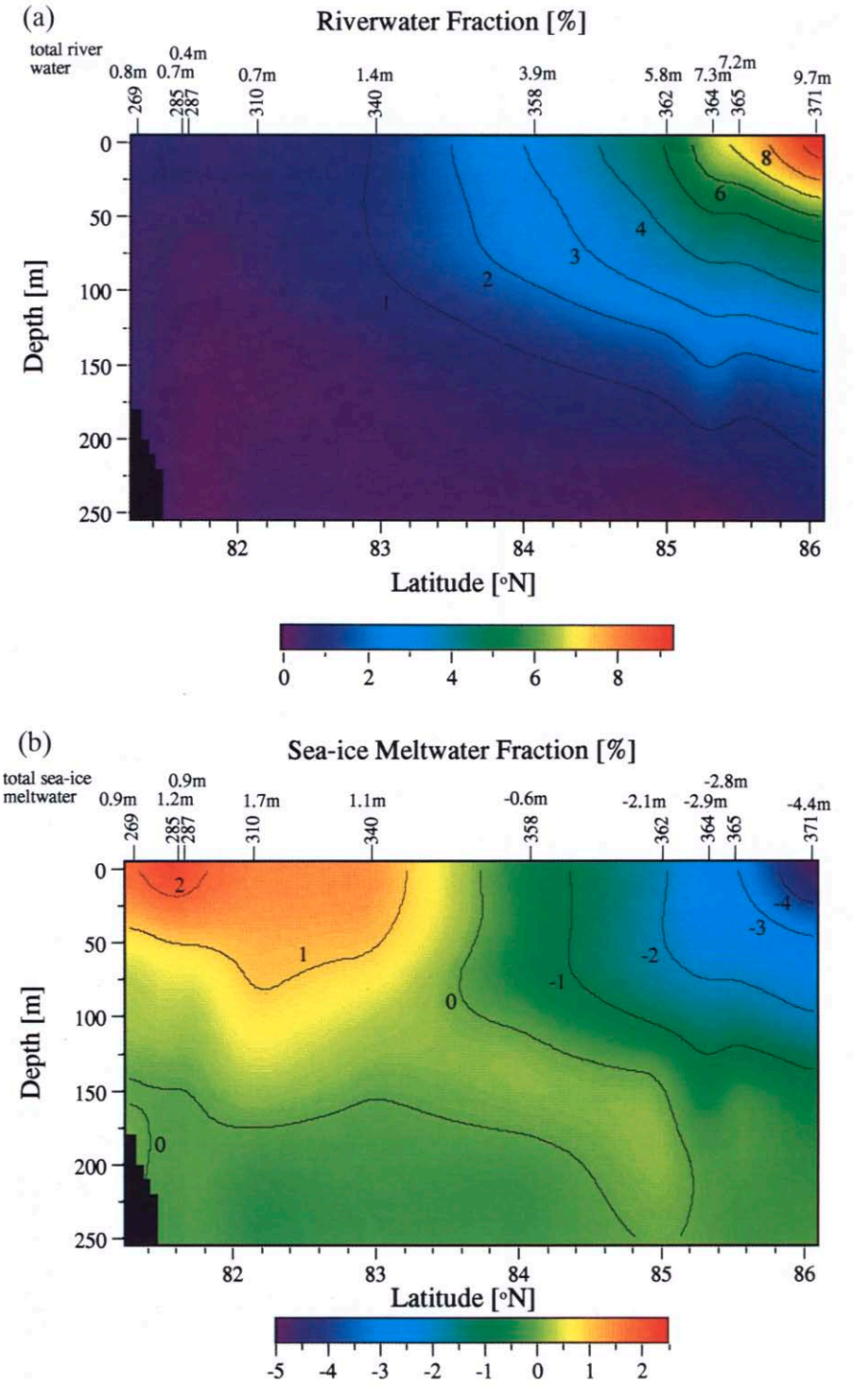

Fig. 6. (a) Same as Fig. 4 for the fraction of river-runoff contained in the halocline water. The fraction of river-runoff is given in percent. (b) Same as Fig. 4 for the fraction (in percent) of sea ice meltwater contained in the halocline waters. Positive numbers mean addition of freshwater by melting of sea ice; negative numbers indicate formation of sea ice (removal of freshwater).

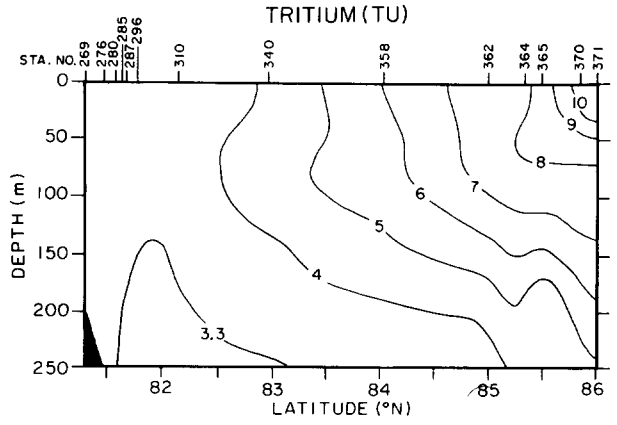

Fig. 4. Tritium section of the upper 250 m of the section extending from the Barents Shelf (Sta. 269) to the Gakkel Ridge (Sta. 371; for geographical position of the stations, see Fig. 1).

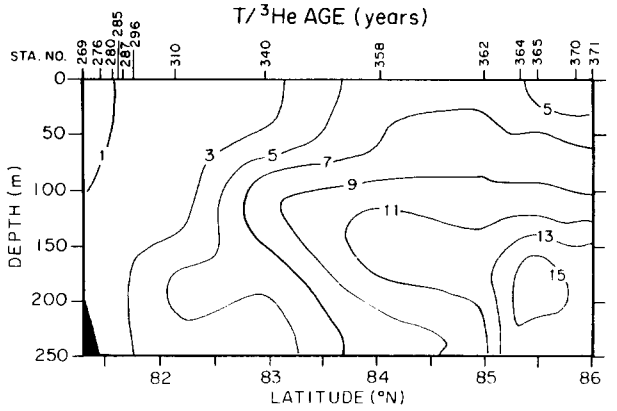

Fig. 5. Same as Fig. 4 for tritium/^{3}He age.

The tritium section (Fig. 4) shows a pattern similar to $\delta^{18}O$ with maximum concentrations of about 10 TU in the surface waters of the northernmost station (Sta. 371) and relatively low concentrations on the Barents Shelf (about 3.5 TU at Sta. 269). The tritium concentrations in the Atlantic water are fairly homogeneous between the Barents Shelf and the northern boundary of the Nansen Basin, with values of about 3.3–4.5 TU.

The apparent $^3H/^3He$-age of the surface water (Fig. 5) increases from the Barents Shelf (about 1 year) towards the northern Nansen Basin where they reach values between about 3 and 5 years at Sta. 371. There is a $^3H/^3He$-age maximum at intermediate depths at stations located in the central Nansen Basin, caused by the fact that relatively young Atlantic water underlies relatively old water of the lower halocline. This feature disappears at stations in the northern Nansen Basin (e.g. Sta. 371) where the Atlantic water is

older than further south. At these northern stations, the $^3H/^3He$-age increases more or less monotonically with depth.

DISCUSSION

River-runoff versus sea ice meltwater

As discussed in detail by ÖSTLUND and HUT (1984), a combined salinity/^{18}O balance can be used to distinguish between river-runoff and sea ice meltwater in the freshwater component of the halocline. The balance is governed by the following equations

$$f_a + f_r + f_i = 1 \quad (1)$$

$$f_a * S_a + f_r * S_r + f_i * S_i = S_m \quad (2)$$

$$f_a * O_a + f_r * O_r + f_i * O_i = O_m. \quad (3)$$

Where f_a, f_r and f_i are the fractions of Atlantic water, river-runoff and sea ice meltwater in a halocline water parcel, and S_a, S_r, S_i, O_a, O_r and O_i are the corresponding salinities and $\delta^{18}O$ values. S_m and O_m are the measured salinity and $\delta\ ^{18}O$ of the halocline water.

For the Atlantic water, the salinity is set to 34.92 and $\delta\ ^{18}O$ to 0.30‰. The choice of the $\delta^{18}O$ value is based on direct measurements by ÖSTLUND and HUT (1984) and on our own data. The $\delta^{18}O$ value for river-runoff ($S_r = 0$) is set to −21% following ÖSTLUND and HUT (1984). The $\delta^{18}O$ values of sea ice (S_i is set to 3‰) are variable (PFIRMAN *et al.*, 1990). This fact has to be taken into account when estimating the $\delta^{18}O$ of sea ice meltwater. As we do not know where the sea ice that contributes to the freshwater component of a specific water parcel is formed, and the $\delta^{18}O$ value of the water from which it is formed is usually unknown, we assume that the sea ice meltwater has the same $\delta^{18}O$ value as the surface water of the station for which the freshwater balance is estimated multiplied by a fractionation factor. ^{18}O fractionation during sea ice formation leads to enrichment of the heavier oxygen isotope in the ice. The fractionation factor for seawater is well known for equilibrium conditions (about 1.0028; BECK and MÜNNICH, 1988). For dynamic conditions under which sea ice is formed in the Arctic Ocean, the fractionation factor is lower. Because we have no reliable data on the sea ice growth rate and the related variable fractionation factor, we use the equilibrium fractionation factor in our calculations. Variations within reasonable limits in the assumptions made for both the $\delta\ ^{18}O$ values of the sea ice meltwater (0 to −2.7‰) and the fractionation factor for sea ice formation (0–2.8‰) affect our estimates of the river-runoff fraction by ±1 and ±0.5%, respectively.

Using equations (1)–(3) and the salinity and oxygen isotope values for the individual water masses, we can calculate the fractions of Atlantic water, sea ice meltwater and river-runoff (Table 1; Fig. 6). Near the Barents Shelf the freshwater component is dominated by sea ice meltwater. The river-runoff fraction in the freshwater increases with increasing distance from the Barents Shelf. At Sta. 358 and at stations further north, the freshwater component consists practically exclusively of river-runoff, and part of the freshwater has been used to form sea ice. The river-runoff signal is a good indicator of the Eurasian Branch of the Transpolar Drift, the southern boundary of which lies close to Sta. 358 (ANDERSON *et al.*, 1989; JONES *et al.*, 1991; PFIRMAN *et al.*, 1990).

Because sea ice formation adds significant amounts of salt but influences the ^{18}O balance only slightly due to the small fractionation factor, the $\delta^{18}O$ versus salinity plot for

Table 1. *List of the hydrographic parameters together with the* $\delta^{18}O$, *tritium, and* ^3He *measurements of halocline waters (salinity <34.5) from the* 1987 Polarstern *section. The fractions of Atlantic water* (f_a), *sea-ice meltwater* (f_i) *and river-runoff* (f_r) *as well as the tritium concentrations in river-runoff calculated from equation* (4) ($^3H_{runoff}$) *are also listed. L stands for samples measured at L-DEO, H for samples measured at Heidelberg*

Sta.	Depth	Θ	Salinity	$\delta^{18}O$	Lab.	^3H	f_i	f_r	f_a	$^3H_{runoff}$	Vintage age	$^3H/^3He$-age
269	3	−1.66	34.094	0.252	L	3.66	2.1	0.5	97.5	—	—	0.4
269	9	−1.66	34.108	0.11	H	3.43	1.4	1.1	97.6	—	—	0.3
269	20	−1.64	34.154	0.241	L	3.55	1.8	0.5	97.6	—	—	0.4
269	40	−1.14	34.450	0.14	H	3.53	0.6	0.8	98.6	—	—	0.7
285	31	−1.70	34.202	0.22	H	3.41	1.6	0.6	97.8	—	—	1.5
287	10	−1.75	34.077	0.274	L	—	2.2	0.4	97.4	—	—	—
287	31	−1.71	34.180	0.241	L	3.53	1.8	0.5	97.7	—	—	0.9
287	40	−1.58	34.248	0.218	L	3.24	1.5	0.6	97.9	—	—	0.7
287	49	−1.22	34.465	0.279	L	2.81	1.2	0.2	98.6	—	—	1.0
310	10	−1.82	34.188	0.210	L	3.57	1.6	0.6	97.8	—	—	1.6
310	29	−1.83	34.217	0.218	L	3.66	1.6	0.6	97.9	—	—	1.6
310	49	−1.83	34.323	0.193	L	—	1.2	0.6	98.2	—	—	—
310	64	−1.79	34.380	0.245	L	3.61	1.2	0.4	98.3	—	—	2.1
310	80	−1.81	34.398	0.250	L	3.56	1.2	0.4	98.4	—	—	1.6
310	94	−1.78	34.437	0.236	L	3.42	1	0.4	98.5	—	—	1.2
340	10	−1.83	34.076	0.119	L	4.07	1.5	1	97.5	—	—	2.4
340	30	−1.83	34.133	0.099	L	4.02	1.3	1.1	97.6	—	—	—
340	50	−1.84	34.181	0.124	L	4.51	1.2	1	97.8	—	—	2.2
340	80	−1.55	34.351	0.088	L	4.89	0.6	1.1	98.3	—	—	7.2
358	15	−1.79	34.028	−0.38	H	6.03	−0.6	3.1	97.5	91.1	13.1	6.4
358	20	−1.79	34.044	−0.343	L	5.89	−0.5	3	97.5	91.0	13.1	7.5
358	44	−1.84	34.199	−0.215	L	5.42	−0.3	2.4	98	92.7	13.3	6.5
358	69	−1.86	34.232	−0.273	L	5.69	−0.7	2.6	98.1	95.3	13.5	7.2
358	89	−1.86	34.235	−0.300	L	5.68	−0.8	2.7	98.1	91.3	13.2	7.2
358	109	−1.49	34.324	−0.033	L	5.44	0.1	1.6	98.3	138.7	17.6	10.8
358	124	−1.241	34.383	0.026	L	4.90	0.2	1.3	98.4	124.8	15.5	10.4
358	138	−0.72	34.450	0.048	L	4.93	0.2	1.2	98.6	138.8	17.6	13.1
362	20	−1.81	33.868	−0.745	L	7.56	−1.9	4.7	97.2	94.7	13.4	6.8
362	40	−1.85	34.112	−0.63	H	—	−2.1	4.2	97.9	—	—	—
362	59	−1.85	34.168	−0.592	L	7.43	−2	4	98	108.2	14.6	9.2
362	74	−1.85	34.181	−0.562	L	7.66	−1.9	3.9	98.1	117.6	15.2	8.3
362	89	−1.83	34.206	−0.52	H	—	−1.8	3.7	98.1	—	—	—
362	104	−1.81	34.216	−0.455	L	—	−1.5	3.4	98.1	—	—	—
362	132	−1.36	34.301	−0.03	H	—	0.2	1.6	98.2	—	—	—
362	147	−1.12	34.351	0.015	L	—	0.3	1.4	98.3	—	—	—
362	162	−0.52	34.449	−0.03	H	—	−0.2	1.5	98.7	—	—	—
364	21	−1.80	33.607	−1.103	L	7.75	−2.9	6.4	96.5	74.9	11.6	5.7
364	30	−1.81	33.686	−0.985	L	8.43	−2.6	5.9	96.7	92.7	13.3	5.0
364	40	−1.84	33.905	−0.839	L	8.43	−2.5	5.2	97.3	104.4	14.2	6.3
364	49	−1.84	33.928	−0.770	L	8.06	−2.2	4.9	97.4	102.9	14	6.2
364	59	−1.84	33.960	−0.793	L	7.93	−2.4	5	97.5	98.6	13.7	6.5
364	69	−1.85	34.078	−0.645	L	8.64	−2.1	4.3	97.8	129.6	15.6	7.4
364	83	−1.85	34.123	−0.599	L	7.57	−2	4.1	97.9	109.8	14.8	8.4
364	148	−1.42	34.282	−0.141	L	6.47	−0.2	2.1	98.2	158.2	19.5	13.6

continued overleaf

Table 1. *Continued*

Sta.	Depth	Θ	Salinity	$\delta^{18}O$	Lab.	^3H	f_i	f_r	f_a	$^3H_{runoff}$	Vintage age	$^3H/^3He$-age
365	25	−1.81	33.580	−1.065	L	8.42	−2.6	6.2	96.4	87.6	12.8	5.1
365	49	−1.84	34.083	−0.714	L	8.47	−2.4	4.6	97.8	118.4	15.2	7.8
365	74	−1.86	34.127	−0.620	L	7.90	−2.1	4.2	97.9	116.0	15.1	8.1
365	99	−1.83	34.171	−0.523	L	7.57	−1.8	3.7	98	119.7	15.3	9.1
365	119	−1.81	34.208	−0.455	L	7.08	−1.5	3.4	98.1	115.4	15.1	9.0
365	138	−1.53	34.258	−0.170	L	—	−0.3	2.2	98.1	—	—	—
365	158	−0.83	34.400	0.008	L	5.66	0.1	1.4	98.5	174.0	19.0	14.9
371	24	−1.80	33.286	−1.58	H	—	−4.3	8.6	95.7	—	—	—
371	40	−1.80	33.289	−1.413	L	8.38	−3.5	7.9	95.6	70.2	11.3	5.2
371	49	−1.84	33.834	−0.892	L	8.63	−2.6	5.5	97.1	103.2	14.1	6.5
371	69	−1.84	34.006	−0.743	L	0.00	−2.4	4.8	97.6	—	—	—
371	83	−1.84	34.063	−0.700	L	7.65	−2.3	4.6	97.7	100.9	13.9	8.3
371	99	−1.85	34.115	−0.661	L	7.59	−2.3	4.4	97.9	103.6	14.1	8.0
371	119	−1.83	34.160	−0.553	L	7.73	−1.9	3.9	98	119.1	15.3	8.8
371	157	−1.19	34.321	−0.16	H	6.59	−0.5	2.1	98.3	158.4	18.5	14.1
371	177	−0.59	34.440	0.016	L	6.73	0	1.3	98.6	260.0	20.2	15.6

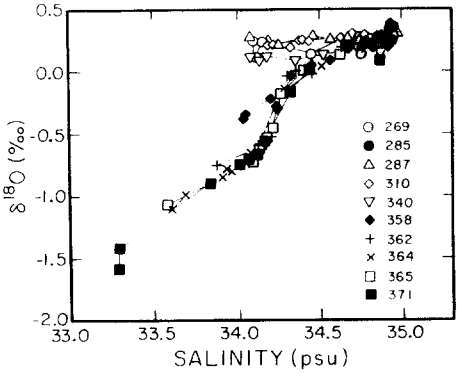

Fig. 7. Salinity versus $\delta^{18}O$ plot (for geographical position of the stations, see Fig. 1).

halocline waters (Fig. 7) is strongly non-linear and is basically meaningless with respect to mixing considerations without additional information.

Tritium vintage ages

The tritium balance of the halocline waters is given by the following equation

$$f_a * T_a + f_r * T_r + f_i * T_i = T_m \tag{4}$$

where T_a, T_r, T_i and T_m mean the tritium concentrations of the Atlantic water, the river-runoff, the sea ice meltwater and the measured halocline water, respectively. As both T_a and T_m are known and T_i can be assumed to be the same as the surface water tritium

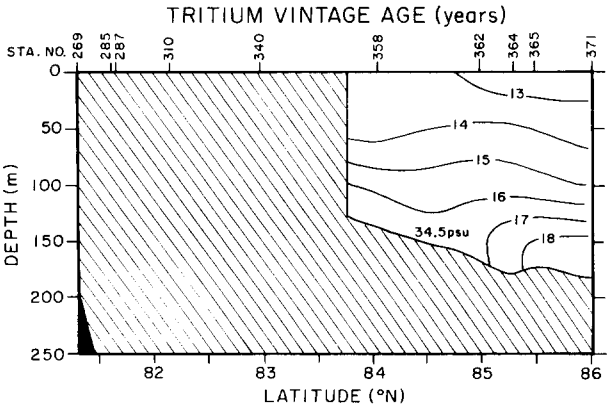

Fig. 8. Same as Fig. 4 for tritium vintage ages. The part of the section in which the river-runoff component used to determine the tritium vintage age is insignificant is shaded.

concentration measured at the individual stations, equation (4) can be resolved for the tritium concentration of the river-runoff component T_r. Comparison of this tritium concentration with the time-dependent tritium curve for river-runoff principally allows estimation of the "vintage" of the river-runoff. This method was used by ÖSTLUND and HUT (1984) to estimate the age of the freshwater component of the Arctic halocline. In our estimates we used values of 3.25 TU for T_a and the surface values measured at the individual stations for T_i (range: 3.7 TU at Sta. 269 to 10 TU at Sta. 371). The calculated tritium concentrations of the freshwater component range from about 20 to about 260 TU (reference year 1987; see Table 1). We did a straightforward comparison of these values with the tritium curve for river-runoff estimated by ÖSTLUND and HUT (1984) using a hydrological model developed by WEISS and ROETHER (1975) extended to 1987 using tritium measurements in precipitation published by the International Atomic Energy Agency. The comparison yields "freight train" ages of the river-runoff component of the freshwater between 9 and 20 years, with a general trend of increasing ages with increasing depth (Fig. 8, Table 1). This range is significantly higher than the values obtained by ÖSTLUND and HUT (1984; 8–10 years) and is similar to the range obtained using other tracers such as CFCs (WALLACE and MOORE, 1985; WALLACE *et al.*, 1987) or tritium/^{3}He (ÖSTLUND *et al.*, 1982; SCHLOSSER *et al.*, 1990; WALLACE *et al.*, 1992).

Comparison of tritium vintage ages and tritium/^{3}He ages

The ages of the freshwater component derived from the tritium data are systematically higher than the tritium/^{3}He ages (Fig. 9). We interpret this difference as an indicator of the mean residence time of the freshwater component on the shelf. Figure 9 suggests a mean residence time of about 8.5 years. Because the freshwater component of the shelf waters leaving the shelves contains a mixture of river-runoff discharged during more than one year, and the tritium concentration in runoff is a non-linear function of time, the difference between the two ages might be misleading if interpreted in a straightforward manner. We therefore calculated the tritium concentration of the freshwater component of the shelf water for different storage times of the river-runoff on the shelf. For this calculation we

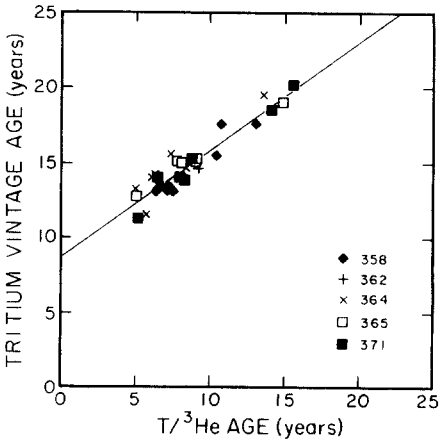

Fig. 9. Tritium vintage age versus tritium/^{3}He age plot for the upper water column ($S > 3.45$).

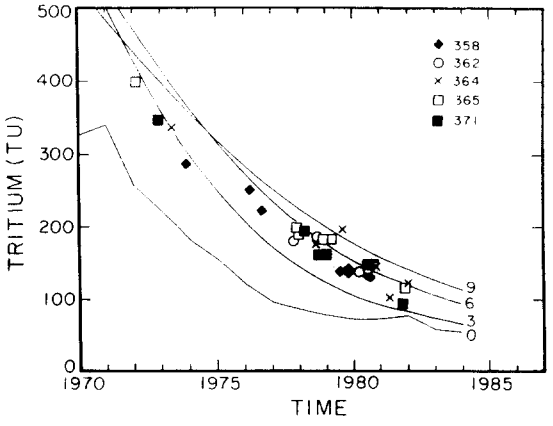

Fig. 10. Tritium concentrations as a function of time in the runoff component of shelfwater for different residence times of the shelf water (one-box model). According to their ^{3}H/^{3}He-age, the calculated tritium values in the runoff component are included in the plot at the time 1987 minus the tritium/^{3}He age for samples with salinities above 34.5. For explanation, see text.

used the tritium curve for Arctic runoff as input function of a well-mixed reservoir (one-box model). The resulting tritium concentrations as functions of time are plotted for several mean residence times of the shelf water (Fig. 10).

We then can compare the river-runoff tritium concentrations estimated using equation (4) to the simulated tritium concentrations of the river-runoff component contained in shelf water. If we assume that the tritium/^{3}He age reflects the time that has passed since the shelf waters entered the halocline, we can plot the tritium concentration of the runoff component contained in the halocline waters on the tritium curve at the time the water left the shelf (1987 minus tritium/^{3}He age; the values plotted on the y axis represent the tritium concentrations at the time of runoff; Fig. 10). Most of the tritium points fall between the curves calculated for mean residence times of the freshwater component on the shelf of 3

and 6 years, respectively, indicating a mean residence time of the river-runoff component of 3–6 years. The box model calculation was checked for consistency with salinity data and good agreement was found.

In most cases the tritium/^{3}He age of the shelf water is not zero due to limited exchange with the atmosphere. Therefore, the difference between the tritium age and the tritium/^{3}He age has to be corrected to obtain a meaningful estimate of the mean residence time of the river-runoff on the shelf. We observed tritium/^{3}He ages at our stations on the Barents shelf and close to the continental slope (269, 280 and 287) in the range of about 0.5–1.5 years. If we correct the difference between the tritium ages and the tritium/^{3}He ages for this initial tritium/^{3}He age, we obtain a best estimate for the mean residence time of the runoff component of about 3.5±2 years. The scatter in our data reflects variations in both the mean residence times and the initial tritium/^{3}He ages of the shelf waters.

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